Fat Saturation for 2D Small-tip Fast Recovery Imaging Using Tailored 3D Spectral-Spatial Pulses

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Introduction: Small-Tip Fast Recovery imaging (STFR) has been proposed recently as a general imaging method for producing high SNR and bSSFP-like image contrast without off-resonance induced banding artifacts [1]. In one variation, this steady-state sequence uses non-slice-selective tailored tip-up pulse at the end of each TR and applies RF spoiling to suppress out-of-slice signals. Like bSSFP, STFR can produce bright (or unpredictable) fat signal, which is generally undesirable. Numerous methods for fat-suppression in bSSFP have been proposed, but existing methods typically require repeated acquisitions, multi-TR approaches, or interruption of the steady-state. An advantage of STFR over bSSFP is that it is easily compatible with fat saturation (sat) preparation, since STFR can be a spoiled sequence. The conventional fat sat techniques that use spectrally selective pulses [2], however, sometimes suffer from inaccurate excitation due to inhomogeneous B_0 or B_1 field. A tailored 4D spectral-spatial (SPSP) pulse with parallel excitation has been proposed to address this problem for 3D space [3]. In this work, we adapt the spectral spatial idea to 2D STFR imaging by applying a fat sat preparation containing a 3D SPSP pulse (2 spatial and 1 spectral dimensions). We discovered a new RF spoiling for 2D STFR with fat sat, which also offers improvements for other RF spoiled sequences equipped with fat sat, e.g., spoiled GRE with fat sat. In this work, we designed a very short tailored 3D SPSP pulse that successfully compensates for 2D B_0 inhomogeneities in phantom experiments with single coil transmission, but this method can be generalized to B_0 and B_1 inhomogeneity compensation using parallel excitation.

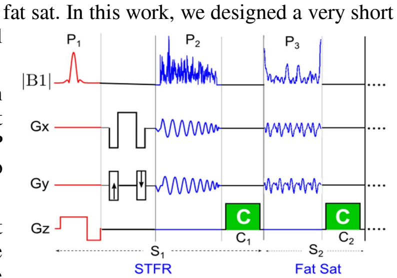

Fig. 1: 2D STFR with fat sat

Theory: Fig. 1 shows the 2D STFR with fat sat sequence, where the typical STFR [1] containing slice-select tip-down pulse (P_1) and 2D tailored tip-up pulse (P_2) with gradient crusher (C_1) is followed by fat sat preparation (P_3 and C_2) that saturates and crushes fat. To compensate for local B_0/B_1 inhomogeneities in a 2D slice, we propose a tailored 3D SPSP pulse for fat sat (P_3) by the same 2-step method proposed in [3] except that repeated 2D spiral-out trajectories are used to cover the 3D SPSP k-space (k_x-k_y-k_f) efficiently.

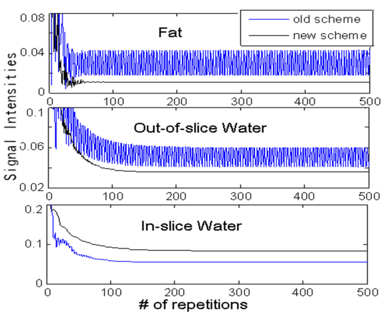

Fig. 2: all the plots share the same legends and x/y labels.

Since 2D STFR is a steady state sequence that has short TR (<T_2), it requires RF spoiling to completely spoil undesired signal outside the slice of interest; so does the fat sat part that needs to completely remove saturated in-slice fat and undesired out-of-slice signal. It has been shown in [1] that regular STFR without fat sat works with the RF spoiling scheme that keeps the same global RF phase for P_1 and P_2 in each TR and applies linear phase increments in every TR, which is similar to conventional RF spoiling [4]; it is because the readout gradients have zero net area so that the whole part that contains P_1 and P_2 can be treated as a single pulse, which becomes the same as the spoiled GRE example in [4]. However, in STFR with fat sat, P_3 is separated by the crusher C_1 from P_1 and P_2, which alters the progression to steady state [4]. To solve this problem, we propose a new RF spoiling scheme, which is to apply linear phase increment in "every part before a crusher" instead of every T_R; in other words, P_1 and P_2 with C_1 are put together as a subpart S_1, P_3 with C_2 is a subpart S_2, and the linear phase increment is applied to the RF pulses in every subpart. As a result, in the *nth* T_R, the global phase of P_1 and P_2 is $\frac{a}{2}(2n-1)^2 + b*(2n-1) + c$ and that of P_3 is $\frac{a}{2}(2n)^2 + b*(2n) + c$, as opposed to $\frac{a}{2}n^2 + bn + c$ for all RF pulses which is the case in the conventional spoiling scheme, where a, b, c are user-defined constants.

Methods and Results: We first demonstrated the necessity of using the new spoiling scheme by Bloch equation simulations. Specifically, we simulated the time evolution of the integrated magnetization of a 0.5 cm voxel with 5000 isochromats. T_R of the sequence was 10 ms, T_1 was set to be 1 s for water and 0.2 s for fat, and the parameter a of the RF phase evolution was 90^0. Fig. 2 shows the signal intensities immediately after each P_1 pulse of 500 repetitions, which is sufficiently long to check steady-state reaching. We simulated for fat, out-of-slice water and in-slice water: fat is tipped 90^0 (in slice) or close to 90^0 (out of slice) by P_3, while water gets no tip (in slice) or small-tip (out of slice) by P_3. There is no need to differentiate in-slice and out-of-slice fat to check steady-state reaching, but water in and out of slice behaves differently as no tipping by P_3 can make a difference. As shown in Fig.2, although the old scheme can make the in-slice water, which only experiences P_1 and P_2, reach steady state, the signals of voxels that experience P_1, P_2 and P_3, i.e., fat and out-of-slice water, cannot reach steady state by the old scheme; whereas, the new spoiling scheme works for every case.

With the new scheme, we compared the proposed 3D fat sat pulse with the conventional Shinnar-Le Roux (SLR) [5] fat sat pulse in a phantom on a 3T GE scanner equipped with a single-channel head coil. We designed 3D fat sat pulses as short as 2.1 ms for 2D axial slices of a cylindrical phantom filled with water and peanut oil, according to the corresponding B_0 maps. The proposed pulse was compared with a 2.1 ms SLR pulse as well as a 5 ms SLR pulse which is standard for 3T scanners. For the 2D STFR sequences with different fat sat pulses, the same tailored tip-up pulse (P_2) was designed according to the B_0 map for water, so it produces irrelevant artifacts in fat parts of the original images without fat sat. Fig. 3 shows the results of 2 different slices of the same object which have very different B_0 maps. Each set of the results shows the B_0 map, the images acquired without fat sat pulses and the ratios between fat saturated images and non-fat-sat images, where readout is Cartesian spin-warp and imaging parameters are: T_R = 19.4 ms for the one with 5 ms fat sat pulse and 16.5 ms for the other two sequences, FOV = 14 cm, and the parameter a for RF spoiling is set to 117^0 empirically. As can be seen in the ratio images: for the water part, the 2.1 ms SLR fat sat fails when off-resonance is negative, and the 5 ms SLR fat sat is relatively robust and only slightly excites water when off-resonance is way smaller than 0; for the fat part, both SLR pulses are relatively robust except that the 5 ms SLR pulse leaves some fat signals in large off-resonance regions; in contrast, the proposed 3D fat sat pulse is generally robust for all cases.

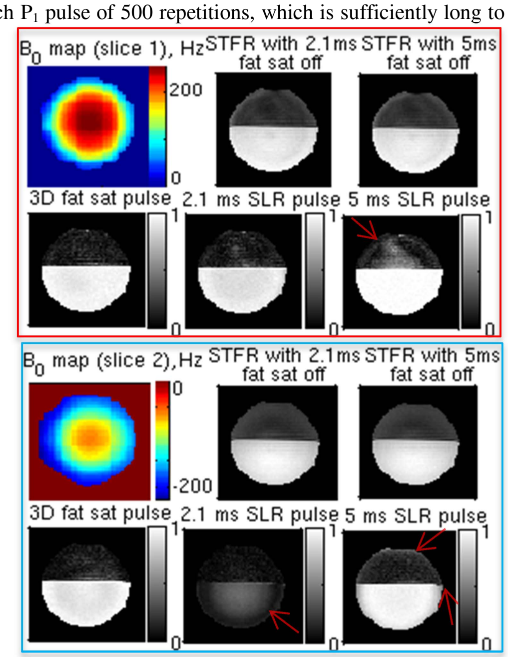

Fig. 3: top rows: B_0 maps, 2 original images; bottom rows: ratio images produced by 3 different fat sat pulses. Results of slice 1 and slice 2 are shown in red and blue box respectively.

Conclusions: We have shown that the 2D STFR with fat sat requires a new RF spoiling scheme to reach steady state. The proposed 3D SPSP fat sat pulse is less than half the length of the standard 5 ms fat sat pulse and we have demonstrated in phantoms that it is more robust to B_0 inhomogeneities, and this design can potentially be generalized to compensate for B_0 and B_1 inhomogeneities with parallel excitation. The proposed 2D STFR with fat sat sequence is a potential alternative to fat-suppressed bSSFP.

References: [1] Nielsen et al., MRM 2012 April. [2] Frahm et al., Radiology 1985: 156. [3] Zhao et al., Proc. ISMRM 20: 636. [4] Zur et al., MRM 1991: 21. [5] Pauly et al., IEEE TMI, 1991: 10. **Acknowledgements**: This work is supported by NIH Grants R01NS58576 and R21EB012674.